Investigation of the coupling paths of a galvanically isolated AC/AC converter

Anne Roc'h[1], Dongsheng Zhao[3], Frank Leferink[1,2], Henk Polinder[3], Braham Ferreira[3]

[1]University of Twente
P.O. Box 214, 7500 AE Enschede
The Netherlands
a.roch@ewi.utwente.nl
frank.leferink@utwente.nl

[2] Thales Netherlands
P.O. Box 42, 7550 GD Hengelo
The Netherlands
frank.leferink@nl.thalesgroup.com

[3]Technical University Delft
P.O. Box 5, 2600 AA Delft
The Netherlands
D.Zhao@ewi.tudelft.nl
J.A.Ferreira@ewi.tudelft.nl

Abstract—**A galvanically isolated three-phase AC/AC converter with a high-frequency AC-link has been analyzed from an EMC point of view. This is a special configuration because of a large number of switches, a high frequency transformer, and a four-wire output. The essential coupling paths are identified. Corresponding suppression remedies are given. The results, before and after measures, have been presented to demonstrate the improvement in EMC.**

Keywords: AC/AC converter; electromagnetic interference; galvanically isolated

I. INTRODUCTION

The EMI generation mechanisms and design rules of DC/DC converters [1], AC/DC converters [2], and DC/AC converters [3] have been extensively investigated and are well known. However, the EMC research on AC/AC converters is mainly limited to converters without electrical isolation [4]-[5] for instance, the converter inside a drive system feeding a motor.

One rapidly growing application of AC/AC converters is to provide an interface between a public power grid and a load. For instance it can be used to power a yacht when it is docked in the harbor. It can also be used to connect a domestic distributed generator to public power network. The AC/AC converters in such applications should be able to

- support a wide variety of input voltages and frequencies;
- provide power conditioning of input power;
- support a variety of applications, including parallel operation with several generators;
- support bidirectional power flowing;
- provide galvanic isolation for optimal safety;
- support single phase input operation;
- support unbalanced load.

To meet all these requirements, the structure presented in Fig.1 is proposed. It consists of a three phase PWM boost rectifier system able to convert the grid three phase system into a DC voltage, a DC capacitor tank in the primary side, a DC/DC converter with isolation transformer, a DC capacitor tank in the secondary side, a three phase inverter system able to generate variable frequency and variable voltage in the three phase system, a control circuit and sensors, protection circuit, a cooling system, and a start up circuit to limit the current charging the DC bus capacitor.

The static switches permit the flexible and bidirectional power flowing through the converter. If we consider an AC input on the left and a load on the right, the first three converter legs of IGBTs (Insulated Gate Bipolar Transistor) work as a PWM (Pulse width Modulation) boost type rectifier and the last four pairs of IGBT work as a PWM inverter. The three phase four wires output provides the capability to feed unbalanced loads. Both the converter and inverter are working with carrier frequency of 5 kHz.

The DC/DC converter is used to provide galvanic isolation between the input and the output. On both sides of the transformer, two pairs of IGBTs are working at 5 kHz. This arrangement also makes the bi-directional power flow possible and the output voltage controllable. The primary and the secondary DC link capacitor tanks consist of sixteen 450 V, 470 µF capacitors, and each two capacitors are connected in series to stand the high DC link voltage up to 780 V. The effective capacitance of the DC-link then becomes 3760 µF.

The AC/DC converter is a commercial-off-the-shelf (COTS) product. It is used to power the drive circuit and the control circuit. The converter has its own EMI filter in the input. The specification of output is 24 Vdc and 10 A. Its switching frequency is 50 kHz.

Sinusoidal filters are added in the input and output sides to give sinusoidal current and voltage to meet the harmonic requirement and reduce the stress for the load. Two common mode chokes are inserted to reduce the common mode (CM) noise level. X and Y capacitors are also provided on input and output sides of the main converter. The filters have not been designed for this application but are COTS.

Besides the functional realization, from an EMC point of view, this structure has some uncommon features which make the investigation interesting. First, there is a sinusoidal filter at the input and another one at the output, but their wiring arrangement has influence on the generation of common mode noise.

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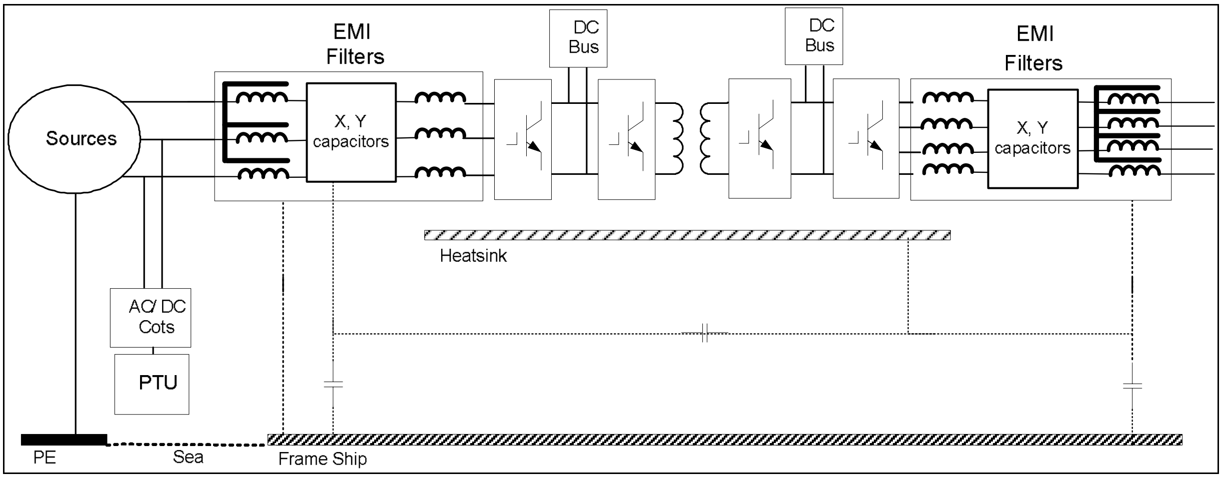

Fig. 1. Diagram of the AC/AC converter with galvanic isolated ac-link

Second, there are 11 pairs of high power IGBT switches mounted on a common heat sink. A high level of noise is expected due to the capacitive coupling between the IGBTs and the heat sink. The method to connect the heat sink to the frame has significant influence in EMC performance.

The essential coupling paths for this kind of AC/AC converter are identified first. Corresponding suppression remedies are proposed and tested via experiments. The result proves the analysis and confirms the improvement in EMC.

II. EMI Generation and Essential Coupling Paths Identification

This structure is new and interesting in an EMC point of view due to the combination of a high frequency AC-link, auxiliary sinusoidal filters, a high numbers of IGBT switches and the floating heatsink. Conventional electromagnetic interference suppression components have already been designed and inserted at inputs and outputs of the converter as indicated in Fig. 1. These components should be efficient enough to reduce or block interferences from the entrance in a traditional three-phase converter. The essential coupling paths will be now investigated.

A. Setup of measurements

A LISN (Line Impedance Stabilisation Network) is inserted between the mains supply 230/400 Volts, 50Hz and the converter. LISN is used for conformity test but is not suitable to identify the noise source. One limitation is that we only do measurements at the input port. Separation of common mode noise and differential noise is also impossible unless the auxiliary circuit is modified. To identify the propagation path of noise source, two current probes, described in Table 1, are also used. Their correction factor has been taken into account in measurements with the EMI receiver.

B. Initial scan

An initial frequency scan, through the LISN, in the second phase is presented in Fig. 2. It presents three issues around 100 kHz, 190 kHz and 4.5 MHz. The scan result in the third phase is identical; however the scan result in the first phase presents one difference: the maximum at 100 kHz is not present.

TABLE 1: INSTRUMENTS USED IN EMI MEASUREMENT

HF/VHF current probe	LF current probe	LISN	Pulse limiter
A.H. systems, Inc	A.H. systems, Inc		R&S
BCP-200/511	BCP-200/510		ESH3Z2
0.1 to 100 MHz	20Hz to 1 MHz	50Ω/50µH V-LISN	10dB Attenuation

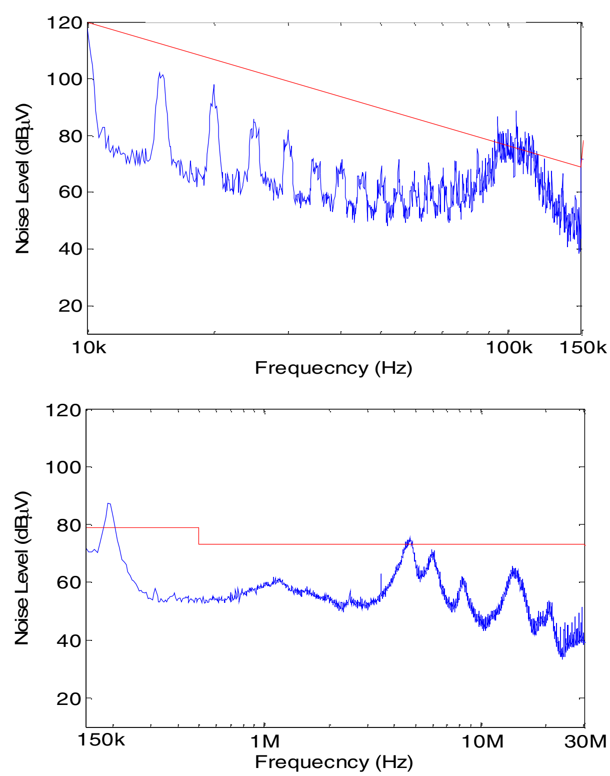

Fig. 2: Initial scan of the second phase through the LISN

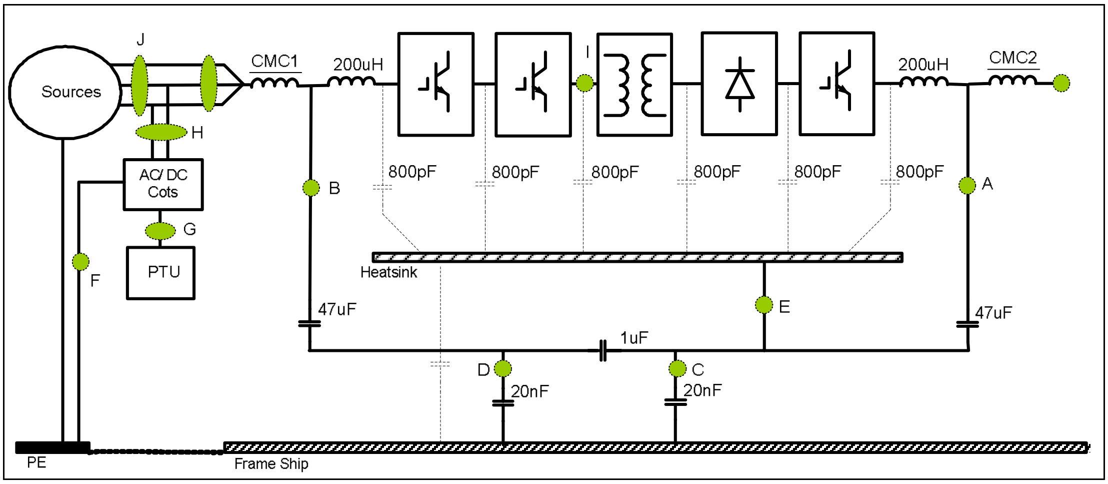

Fig. 3: Equivalent circuit for the common mode current

C. *EMI generation mechanism*

The common mode and the differential mode current have been measured in 12 key points of the converter. These points are marked by letters from (A) to CMC2 and are shown in Fig. 3.

The point (J) is selected at the line cable of the converter. The common mode measurement result at this point is shown in Fig. 4. It is obvious that the result from LISN has the same trends as the result measured by CM current in the frequency band from 150 kHz to 30 MHz, except for a factor caused by the measuring resistor of the LISN. We can conclude that the noise paths above 150 kHz are related to common mode noise.

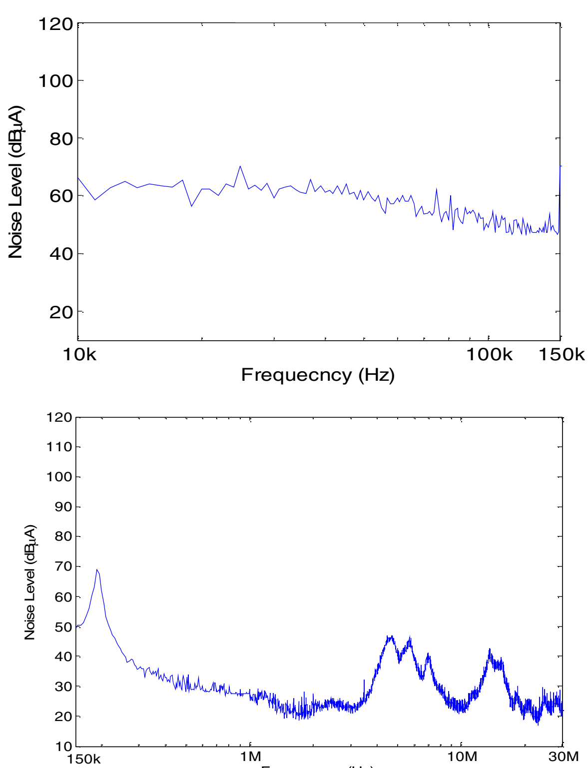

Fig. 4: CM current scan of the line cable

By contrast, the differential mode current is the dominant source below 150 kHz.

It can be explained by the fact that most of the differential mode noise is under control due to traditional filter components already included in the structure, as presented in Fig.1. These electromagnetic interferences filters brings additional noise loop for the common mode noise flowing through the heat sink and the frame. Without understanding the mechanism of such a loop, the EMC performance of the converter is hard to be controlled with the various connecting method of the floating heat sink.

III. ANALYSIS

The Table 2 indicates the level of common mode current for each point of interest.

TABLE 2: CM NOISE LEVEL IN EACH TEST POINT

Test points	**CM noise current level in the frequency range (dBµA)**			
	80kHz-120kHz	***190kHz***	***Around 2MHz***	***Around 4.52MHz***
(A)	110	117	68	80
(B)	N.A.	116	65	81
(C)	60	94	73	68
(D)	65	95	71	76
(E)	80	122	67	75
(F)	N.A.	92	43	62
(G)	N.A.	91	42	66
(H)	N.A.	40	27	45
(I)	100	90	82	99
(J)	50	69	27	47
CMC1	N.A.	66	23	30
CMC2	N.A.	60	25	27

It is observed from the measurement results, that all maxima in the frequency spectrum appear in four frequency ranges. This is listed Table. 2. It is assumed that four loops are created by the structure of the converter.

Measurements of common mode currents show the following distinct facts:

For each frequency range, there are some points with a highest level of the noise. They are the noise source, also called resonance loop [4]. The noise source couples to the surrounding. The levels of the noise currents away from the noise source are usually extremely low, that means the coupling can be treated as uni-directional for these kind of weak couplings. The transfer ratio can be defined to quantify the EMC performance.

The general behavior of the structure is also interesting by its symmetry: the level of noise is the same between the pairs (A) and (B), and (C) and (D). This is due to the symmetrical design of the structure.

A. Coupling path with heatsink connected to neutral

Measurement points of interest in the loop 1, in descending ordered by magnitude, are: (A) and (B), (H) and (J), and (C) and (D). A common mode loop current is flowing between 80 kHz and 120 kHz in the main converter. The current is flowing from the output terminals of IGBTs, through the DM inductor, the DM sinusoidal filtering capacitors of 47 µF, and coming back through the DM inductor in the input side and flow through the IGBTs and the capacitor between the primary and secondary winding of the HF transformer.

The level of current in this loop has been measured at 300 mA. A differential mode current is generated by electromagnetic field coupling with the entrance of AC/DC converter. This differential mode current is mixed with the differential mode current of PWM inverter input. That makes the two phases connecting the COST AC/DC converter to have much higher noise level between 80 kHz and 120 kHz.

Observing the loop 2, the noise levels of these interesting points are ordered as, (E), (A) and (B) and all the others points below 95 dBµA. This leads us to identify that the second path (loop 2) is composed of a common mode current flowing between 150 kHz and 300 kHz. In point (E), the major noise path in this structure, the current amplitude is up to 1.3A. The current is flowing symmetrically on both sides of the IGBTs, through the inductor and the 47 µF (and 1 µF for the left side), to reach the heatsink via the direct link with the neutral. The current then comes back to the IGBTs via capacitive coupling between drains of the IGBTs and the heat sink.

In the third path only 2 points present a maximum: (C) and (D). Levels of (I), (E), (A), (B), are flat in the frequency range from 800 kHz to 1.5 MHz, the others points present negligible level of currents. These facts lead us to conclude that in this frequency range the same phenomena described for the loop 2 also occurs here but in a minor proportion. The maximum visible around the 20 nF Y capacitors is due to a resonance with a parasitic inductance from wiring. The third path (loop 3) is so a common mode current flowing around 2 MHz and is composed of the two Y-capacitors of 20 nF and the capacitors of 1 µF. This loop is not a main issue in the measurement through the LISN because the level of current involved fits requirements and most of the conducted noise generated by this loop is contained within the converter.

The main noise current measured at 4.52 MHz is in (I). In (A) and (B) and (D) and (C) the level of CM current is between 60 dBµA and 80 dBµA. The fourth path (loop 4) is composed of a common mode current flowing in the loop through the inductors, the DM filtering capacitor and 20 nF capacitors. By electromagnetic coupling a common mode current is generated in the loop formed by the AC/DC, the LISN and the ground.

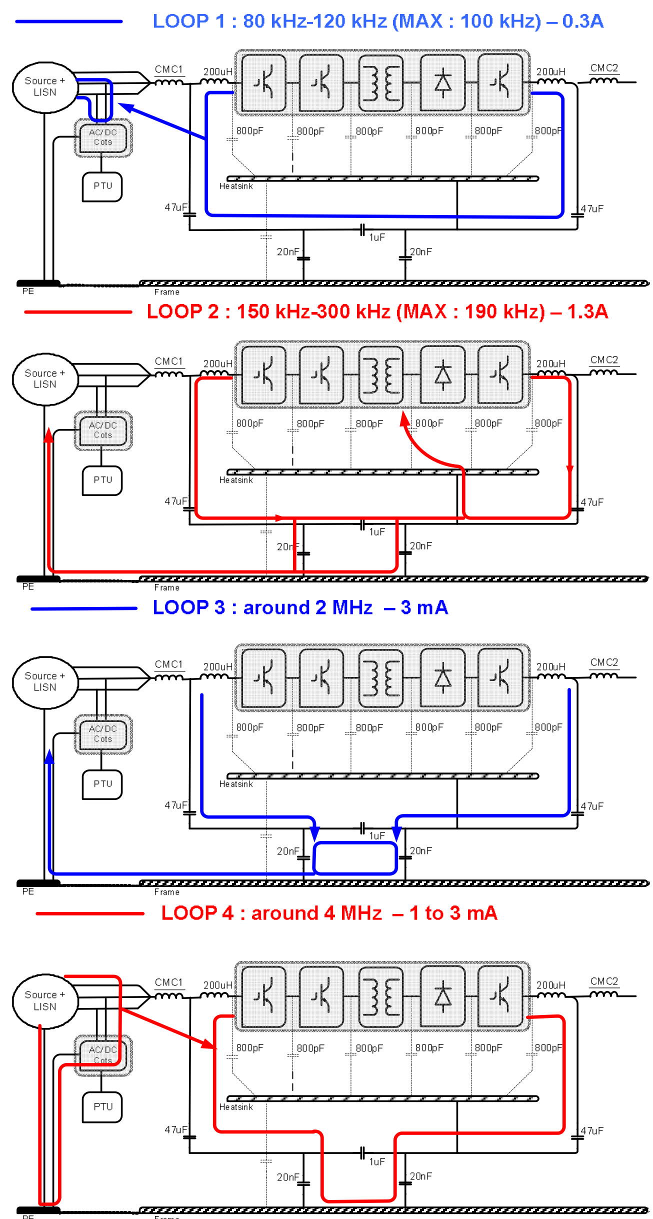

Fig. 5: Main paths of conducted interferences

A synthesis on the paths identified in this structure can be that the connection of the heatsink to the neutral has lead to the usage of the 1 µF capacitors in the configuration illustrated in Fig. 3. This configuration provides a main loop for the noise coming from the IGBTs and the transformer to flow in a small loop within the converter. Depending of the frequency, this main loop will resonate with the 20 nF Y capacitors, coupled by capacitive coupling with the IGBTs or coupled with the secondary circuit composed of the COTS AC/DC and the LISN.

B. Comparison with a grounded heatsink

In this part the heatsink is grounded to the frame. The idea is to check the advantage, or disadvantage with respect to not having the heatsink connected with the ground.

The point (D) becomes a good indicator in this new configuration. Its scan is presented in Fig. 6. The level of common mode current is lifted around 10 dB above the level of the situation with a floating heatsink) until 1.5 MHz, except at 600 kHz where the level is the same (increasing faster again after). After 1.5 MHz frequency the level of current in (D) is the same as with the floating heatsink. The level of common mode current in (D) also remains the same below 150 kHz .This leads to the conclusion that the coupling with the heatsink, in the initial setup, occurs from 150 kHz until 1.5 MHz. At this frequency 20 nF Y capacitors are a part of a new resonance loop for the common mode current in the two setups, identified as the loop 3.

Regarding the level of noise at the input of the LISN for the phase 2 and 3, it remains the same below 150 kHz. Between 150 kHz and 300 kHz, the noise from the former loop 1 is much higher (around 10 dB higher). Between 600 kHz and 3 MHz the level of noise is higher and flat at 65 dBµV (plus 10 dB compared to the former loop). A shift of the resonance from 190 kHz to 200 kHz can be observed due to additional parasitic inductances

The floating heatsink, in Fig. 3, seems to keep the loop 2 within the converter, and prevent too much noise from flowing to the frame through the heatsink. With the grounded heatsink the capacitor at 1 µF seems playing a key role: on one hand it allows the loop 1 and 4 to settle within the converter, on the other hand the noisiest loop 2 is maintained within the converter and avoids this high level of common mode current to reach the LISN through the frame. We can expect that to remove this capacitance will increase the noise at 190 kHz and decrease the noise at 100 kHz and 4 MHz.

C. Solutions to control the conducted interferences

Different solutions have been investigated to prevent the noise from flowing through the LISN without changing the actual structure of the converter and its electromagnetic filter in order to keep the advantages of differential mode already under control, and to keep the main loop 2 within the converter.

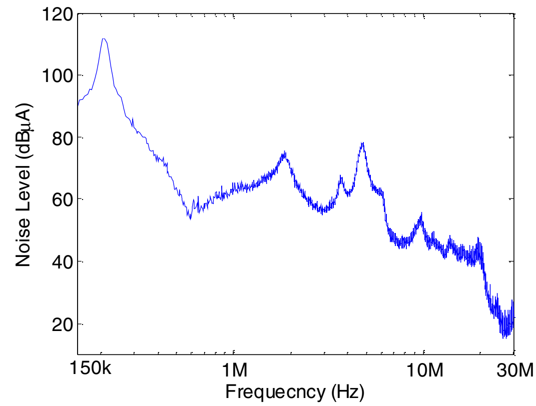

Fig. 6: Scan of the point D, with a grounded heatsink

The reduction of the level of current involved in the loop 1 cannot be done by adding a Y or a X capacitor within the converter, for instance additional Y capacitors between the neutral and the frame may result in overload of the IGBTs[6]. So the idea is too keep the common mode current within the converter and to reduce the differential mode current seen by the LISN. The differential mode in the loop 1 is attenuated by adding an X capacitor of 470 nF at the entrance of AC/DC. The final level of interferences measured through the LISN is now nearly the same between phase 1 and the two others phases under considerations.

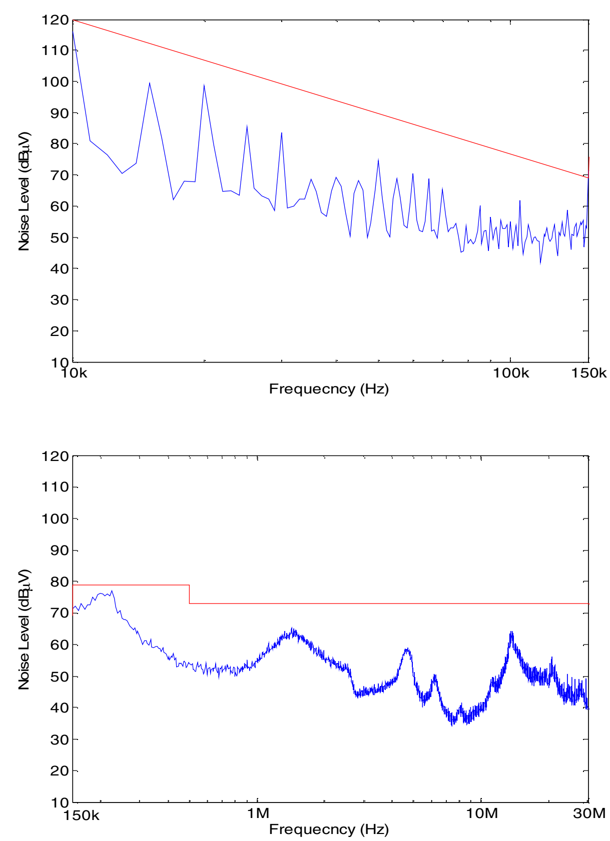

Fig. 7: Final scan of the second phase through the LISN

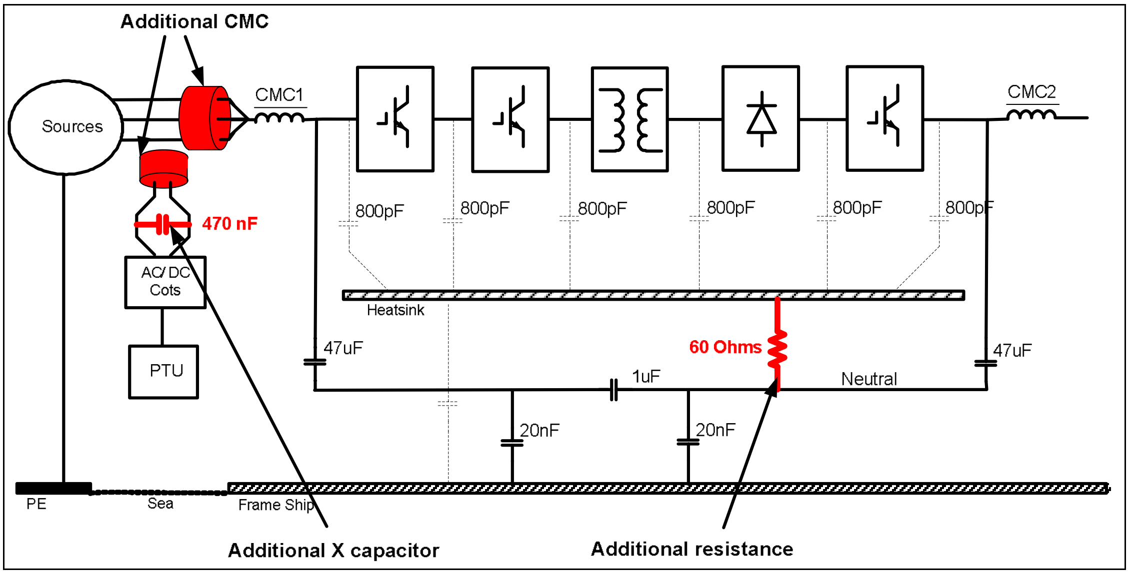

Fig. 8: Final structure of the converter

As explained before, the addition of capacitors to reduce the current in the loop 2 which has the same initial path of the loop 1, can compromise the behavior of the converter itself. In [7], in the case of a traditional 3 phase power supply, a dump resistance has been added between the ground and an artificial ground plane. In the same manner we propose to reduce the level of current which reaches the heatsink by adding a dump resistance between the heatsink and the neutral. The Fig. 6 shows the attenuation with a resistance of 60 ohms (1 W).

The loop 3 is not a major source of interferences, only a few mA are reaching the LISN and requirements are still met. The loop 4 is attenuated with two common mode chokes placed at the input of the COTS AC/DC and at the input of the main converter. The approach is the same as in the first two loops; we propose to reduce the common mode current on the AC/DC side.

The Fig. 7 presents the level of electromagnetic interferences at the second phase of the LISN. In this configuration we have added two common modes chokes at the input of the main converter and the output of the AC/DC converter, a dump resistance of 60 Ω between the heat sink and the neutral and a X capacitor at the entrance of the AC/DC converter. The improvement of the EMC performance is clear with a reduction of 40 dB at 100 kHz, 15 dB at 190 kHz and 25 dB at 4.5 MHz. The Fig. 8 presents the final structure of the converter with the additional components.

IV. Conclusion

A galvanic isolated 3 phases AC/AC converter with a high frequency AC-link has been analyzed. Main paths of conducted interferences have been identified and corresponding suppression solution has been given.

V. Acknowledgement

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